

Azimuthal anisotropy (v_2) of high- p_T π^0 and direct γ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract. Preliminary results from the STAR collaboration of the azimuthal anisotropy (v_2) of π^0 and direct photon (γ_{dir}) at high transverse momentum (p_T) from Au+Au collisions at center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV are presented. A shower-shape analysis is used to select a sample free of direct photons (π^0) and a sample rich in direct photons γ_{rich} . The relative contribution of background in the γ_{rich} sample is determined assuming no associated charged particles nearby γ_{dir} . The v_2 of direct photons ($v_2^{\gamma_{dir}}$) at mid-rapidity ($|\eta^{\gamma_{dir}}| < 1$) and high p_T ($8 < p_T^{\gamma_{dir}} < 16$ GeV/c) is extracted from those of π^0 and neutral particles measured in the same kinematic range. In mid-central Au+Au collisions (10-40%), the v_2 of π^0 ($v_2^{\pi^0}(p_T)$) and charged particles ($v_2^{ch}(p_T)$) are found to be ~ 0.12 and nearly independent of p_T . The measured $v_2^{\gamma_{dir}}(p_T)$ is positive finite and systematically smaller than that of π^0 and charged particles by a factor of ~ 3 . Although the large $v_2^{\pi^0}$ at such high p_T might be partially due to the path-length dependence of energy loss, the non-zero value of $v_2^{\gamma_{dir}}$ indicates a bias of the reaction plane determination due to the presence of jets in the events. Systematic studies are currently in progress.

1. Introduction

The azimuthal distribution of the produced particles in heavy-ion collisions is expected to be sensitive to the initial geometric overlap of the colliding nuclei, and would result in anisotropic azimuthal distributions with respect to the reaction plane. The standard method to quantify the azimuthal anisotropy is to expand the particle azimuthal distributions in a Fourier series $\frac{dN}{d\phi} = \frac{1}{2\pi}[1 + \sum_n 2v_n \cos(n(\phi_{p_T} - \phi_{RP}))]$, where ϕ_{p_T} is the azimuthal angle of the produced particle with certain value of p_T , ϕ_{RP} is the azimuthal angle of the reaction plane, and v_n is the coefficient of the n^{th} harmonic. The 2^{nd} Fourier moment ($n = 2$) is referred to as the “elliptic flow” parameter v_2 and its differential form is given by

$$v_2(p_T) = \langle e^{2i(\phi_{p_T} - \phi_{RP})} \rangle = \langle \cos 2(\phi_{p_T} - \phi_{RP}) \rangle \quad (1)$$

where the brackets denote statistical averaging over different events.

While RHIC data show large amount of elliptic flow as predicted by the hydrodynamic models at low p_T , the results at high p_T deviate strongly from the hydrodynamic predictions as is expected [1]. The medium-induced radiative energy loss of partons (jet-quenching) has been proposed as the source for the large observed azimuthal anisotropy at high p_T , due to the path-length dependence of the parton energy loss [2]. The STAR results [3] show the amount of v_2 at high p_T is larger than the predicted values by pure jet-quenching models. Although recent

measurements by PHENIX [4] show the produced π^0 's in-plane outnumber those produced out-of-plane which may be consistent with the path-length dependence of energy loss, the reaction plane determination might have remaining bias toward the direction of the produced jets. STAR results show insensitivity of the path-length-dependence of energy loss [5] at high p_T through a comparison between γ_{dir} -charged particles and π^0 -charged particles azimuthal correlations.

The v_2 measurement of direct photons would help to assess any remaining bias in the reaction plane determination leading to a positive v_2 signal. Furthermore the $v_2^{\gamma_{dir}}$ would give additional information to help disentangle the various scenarios of direct photon production through the expected opposite contributions to the v_2 [6, 7, 8, 9], and therefore could help to confirm the observed binary scaling of the direct photon [10].

2. Analysis and Results

2.1. Electromagnetic neutral clusters

The STAR detector is well suited for measuring azimuthal angular correlations due to the large coverage in pseudorapidity ($|\eta| < 1$) and full coverage in azimuth (ϕ). While the Barrel Electromagnetic Calorimeter (BEMC) [11] measures the electromagnetic energy with high resolution, the Barrel Shower Maximum Detector (BSMD) provides fine spatial resolution and enhances the rejection power for the hadrons. The Time Projection Chamber (TPC) [12] identifies charged-particles, measures its momenta, and allows for a charged-particle veto cut with the BEMC matching. Using the BEMC to select events (*i.e.* “trigger”) with high- p_T γ , the STAR experiment collected an integrated luminosity of $535 \mu\text{b}^{-1}$ of Au+Au collisions in 2007. In this analysis, events having primary vertex within ± 55 cm of the center of TPC along the beamline, and with at least one electromagnetic cluster with $E_T > 8$ GeV are selected. More than 97% of these clusters have deposited energy greater than 0.5 GeV in each layer of the BSMD. A trigger tower is rejected if it has a track with $p > 3.0$ GeV/ c pointing to it, which reduces the number of the electromagnetic clusters by only $\sim 7\%$.

2.2. v_2 of neutral and charged particles

The v_2 is determined using the standard method (Eq. 1), which correlates each particle with the event plane determined from the full event minus the particle of interest. The event plane is determined by

$$\phi_{RP} = \frac{1}{2} \tan^{-1} \left(\frac{\sum_i \sin(2\phi_i)}{\sum_i \cos(2\phi_i)} \right) \quad (2)$$

where ϕ_i are the azimuthal angles of all the particles used to define the event plane. In this analysis, the charged-track quality criteria are similar to those used in previous STAR analyses [13]. The event plane is measured twice: 1) using all the selected tracks inside the TPC (full-TPC), and 2) using the selected tracks in the opposite pseudorapidity side to the particle of interest (off- η) in order to reduce the “non-flow” contributions (azimuthal correlations not related to the reaction plane). Since the event plane is only an approximation to the true reaction plane, the observed correlation is divided by the event plane resolution. The event plane resolution is estimated using the sub-event method in which the full event is divided up randomly into two sub-events (for full-TPC and off- η separately) as described in [14]. Biases due to the finite acceptance of the detector, which cause the particles to be azimuthally anisotropic in the laboratory system are removed according to the method in [15].

Figure 1 (left panel) shows the v_2 of charged particles (v_2^{ch}) at low p_T using the event plane method (off- η) compared to previous STAR measurements [13], and the v_2 of the charged and neutral particles using the full-TPC and off- η event plane methods at high p_T . At low p_T the $v_2^{ch}(\text{off-}\eta)$ is smaller than the v_2 using the full TPC and agrees well with the $v_2\{4\}$ (4-particle cumulant) method, in which the contribution of the non-flow is expected to be small. At high

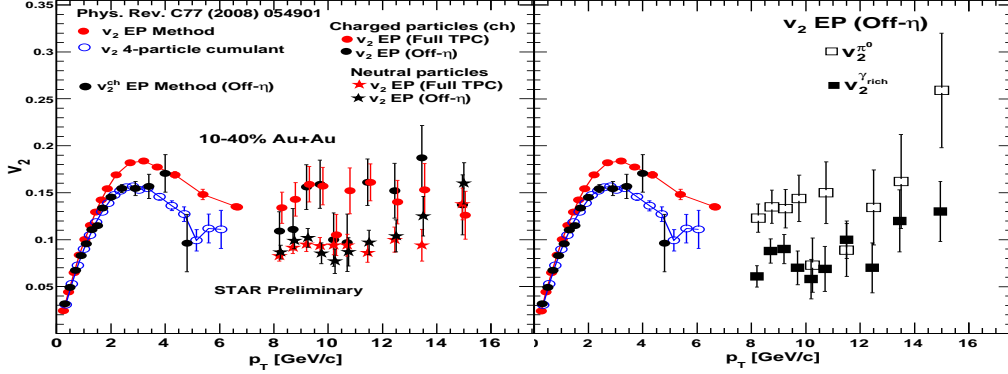


Figure 1. (Color online) For $p_T < 6$ GeV/ c , both panels show previous STAR measurements [13] of v_2 as a function of p_T for charged particles with $|\eta| < 1$ in 10-40% $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV using the Event-Plane method (closed red circles), and the 4-particle cumulant method (open circles). Also v_2 for charged particles ($|\eta| < 1$) using off- η event plane method is shown in closed black circles (this analysis). For $p_T > 6$ GeV/ c : (left panel) v_2 of charged particles (red and black circles) and v_2 of neutral particles (red and black stars) using the full TPC and off- η event plane methods respectively; (right panel) v_2 of π^0 and γ_{rich} (open and closed squares, respectively) using the off- η method.

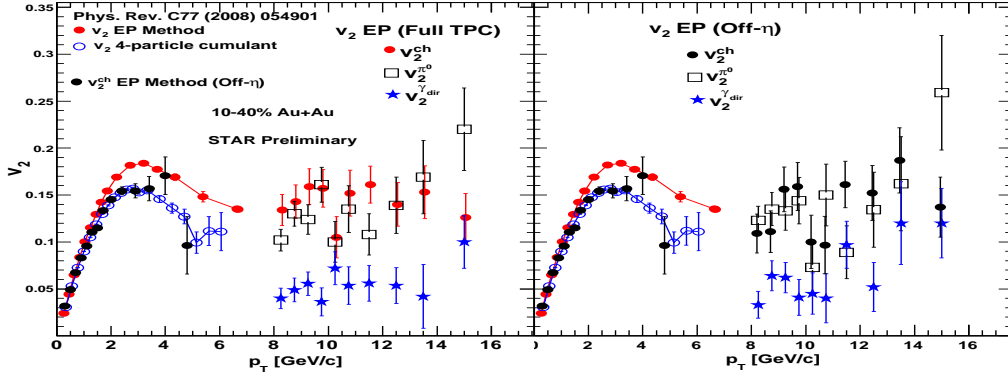


Figure 2. (Color online) For $p_T < 6$ GeV/ c , both panels show measurements as in Fig. 1. For $p_T > 6$ GeV/ c , both panels show v_2 of charged particles, π^0 , and γ_{dir} (circles, squares, stars respectively) using the full TPC (left panel) and using off- η methods (right panel).

p_T the two different methods (full TPC and off- η) for the reaction plane measurements give similar results (both for the charged and neutral particles separately), which might indicate the dominance of non-flow contributions in v_2 measurements. The $v_2(p_T)$ of the neutral particles show systematically smaller values than those of charged particles due to the γ_{dir} contributions.

2.3. Transverse shower profile analysis

A crucial part of the analysis is to discriminate between showers from γ_{dir} and two close γ 's from high- p_T π^0 symmetric decays. At $p_T^{\pi^0} \sim 8$ GeV/ c , the angular separation between the two γ 's

resulting from a π^0 decay is small, but a π^0 shower is generally broader than a single γ shower. The BSMD is capable of $(2\gamma)/(1\gamma)$ separation up to $p_T^{\pi^0} \sim 20$ GeV/ c due to its high granularity. The shower shape is quantified as the cluster energy, measured by the BEMC, normalized by the position-weighted energy moment, measured by the BSMD strips [5]. The shower profile cuts were tuned to obtain a nearly γ_{dir} -free (π_{rich}^0) sample and a sample rich in γ_{dir} (γ_{rich}). Since the shower-shape analysis is only effective for rejecting two close γ showers, the γ_{rich} sample contains a mixture of direct photons and contamination from fragmentation photons (γ_{frag}) and photons from asymmetric hadron (π^0 and η) decays.

Figure 1 (right panel) shows the v_2 of γ_{rich} sample and v_2 of the sample free of direct photons (π^0) using the off- η event plane method. As expected, the v_2 of γ_{rich} sample is smaller than that of π^0 , while the $v_2^{\pi^0}$ is similar to v_2^{ch} which indicates the π^0 sample identified by the transverse shower-shape analysis, to be free of γ_{dir} .

2.4. v_2 of direct photons

The $v_2^{\gamma_{dir}}$ is given by:

$$v_2^{\gamma_{dir}} = \frac{v_2^{\gamma_{rich}} - \mathcal{R}v_2^{\pi^0}}{1 - \mathcal{R}} \quad (3)$$

where $\mathcal{R} = \frac{N^{\pi^0}}{N^{\gamma_{rich}}}$, and the numbers of π^0 and γ_{rich} triggers are represented by N^{π^0} and $N^{\gamma_{rich}}$ respectively. The value of \mathcal{R} is measured in [5] and found to be $\sim 30\%$ in central Au+Au. In Eq. 3 all background sources for γ_{dir} are assumed to have the same v_2 as π^0 . Thus, excepting those γ_{frag} that have no near-side yield, all other sources of γ_{dir} 's background are removed.

Figure 2 (left and right panels) shows the $v_2^{\gamma_{dir}}$ and $v_2^{\pi^0}$ compared to v_2^{ch} at high p_T using the two different event-plane methods. While the $v_2^{\pi^0}$ and v_2^{ch} are similar ($\sim 12\%$), the $v_2^{\gamma_{dir}}$ is systematically lower than that of hadrons. The similarity of the v_2 results using the full-TPC and off- η at high p_T , along with the non-zero value of $v_2^{\gamma_{dir}}$, indicate the non-flow contributions to the measured v_2 .

3. Conclusions

The STAR experiment has reported the first $v_2^{\gamma_{dir}}$ at high- p_T at RHIC. The non-zero value of $v_2^{\gamma_{dir}}$ is probably due to contributions from non-flow to the standard method of v_2 measurements, where the pseudorapidity gap between the particle of interest and the particles used for the reaction plane determination is smaller than two units in pseudorapidity. The positive value of $v_2^{\gamma_{dir}}$ demonstrates the negligible contribution of jet-medium photons [7] and possible contributions of γ_{frag} [6] to the direct photon productions over the covered kinematics range.

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